NON-DESTRUCTIVE TESTING OF DRILLED SHAFTS AND CFA PILES – CURRENT PRACTICE AND NEW METHOD

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Quality control of drilled shafts and CFA piles is greatly dependent upon the practices of the site personnel. In many applications it is difficult or not possible to fully inspect the shaft prior to concreting, such as when the shaft is drilled under slurry. CFA piles are cast with no ability to inspect the shaft prior to concreting. There are numerous methods currently available to assess the integrity of drilled shafts and CFA piles. This paper will compare evaluations by three existing non-destructive test (NDT) methods with a new method of Thermal Integrity Profiling for assessing integrity in drilled shafts and CFA piles. This Thermal Integrity Profiling method determines the integrity over 100% of the shaft cross section, both inside and outside the reinforcing cage, by measuring the hydration temperature of the concrete along the length of the shaft. These temperature measurements are made typically only 12 to 48 hours after concrete placement, thus accelerating the construction process. Thermal Integrity Profiling will be described in detail and the Thermal Integrity Profile (TIP) results from several shafts with purpose built defects will be discussed along with several case histories from drilled shafts and CFA piles where Thermal Integrity Profiling was used. The case histories will compare TIP with various other NDT tests utilized on these particular piles including comparisons with Low Strain Integrity Testing and Cross Hole Sonic Logging. Test results for the various methods will be discussed and the excavation of the upper portion of one drilled shaft will be shown and discussed.

Introduction

Drilled shafts can be a desirable foundation element in many applications due to the large axial and lateral capacities which are attainable for very large drilled shafts. Drilled shafts can be cast in a dry hole which allows for inspection of the hole prior to casting, but the casting process is very difficult to nearly impossible to inspect with any accuracy. Drilled shafts are frequently cast under slurry as a means to stabilize the surrounding soils during the construction process. When casting a drilled shaft under slurry, it is very difficult to accurately inspect the hole prior to casting and it is equally difficult to inspect the shaft during the casting process. CFA piles are another popular choice for their relative ease and speed of installation. The trend has been larger CFA piles carrying greater loads, which makes quality control critical for these piles. Many of the above mentioned processes are blind to inspection and therefore the chances increase for having defects present in the completed elements.

There are several methods available for integrity testing completed elements. Each of these methods has advantages and limitations with no one method yielding 100% testing of the entire element. Some test methods can test the integrity within a small proximity of an access tube while others will test the shaft core but do not test the areas outside the reinforcing cage (concrete cover). A new integrity testing method has recently emerged which is based upon patented research conducted by Professor Gray Mullins with the University of South Florida. This new method involves measuring the heat generated in the element during the hydration process to determine the pile integrity.

This Thermal Integrity Profiling (TIP) method has the ability to evaluate the entire cross-section of the element under test, along the entire shaft length, allowing for verification of concrete cover while also evaluating the core of the shaft. Pile length to diameter ratios which can restrict other integrity testing methods are not a restriction to the TIP method. Additionally, the TIP method is not limited by non-uniform shapes that can occur by design or unintentionally during the construction process. This paper will discuss the current state-of-practice for integrity testing of drilled shafts and CFA piles and will detail this new TIP method. An example will be included showing how the TIP method is used in practice.

Current Shaft Integrity Testing methods

Typical integrity test methods currently being utilized for drilled shafts include the low strain pile integrity test and the cross hole ultra-sonic test. The gamma logging test is another available method but is not as widely used as the low strain integrity test and cross-hole sonic logging (CSL). The low strain pile integrity test method involves attaching an accelerometer to the pile top (typically using wax) and striking the pile top surface with a small handheld hammer. The hammer strike creates a compressive wave within the pile which will reflect off the pile toe and return to the pile top where this return signal is measured by the accelerometer. Changes in the pile cross-section (necking or bulging) will also cause a reflection in the input compressive wave which will be measured by the accelerometer. These return signals due to changes in cross-section will arrive at the surface earlier than the expected pile toe reflection. This low strain integrity test will reveal major defects within a pile. This test is useful in that it is very fast and economical, requiring no special construction techniques (no access tubes required, etc.). One individual can test any or all piles on a site. Non-uniformities will cause reflections which can complicate data interpretation. Bulges located near the pile top can create multiple reflections which can make it difficult to assess the integrity of the shaft below this point. As the length to diameter ratio increases beyond approximately 30, it can be difficult to get a reflection from the pile toe thus leaving the lower section of the pile potentially untested. Additionally, any reinforcing materials which are extending significantly above the pile top can cause vibrations which could interfere with waves traveling within the pile.

The Cross Hole Sonic logging test requires that access tubes be planned into the shaft prior to casting. If the access tubes are not planned into the construction, the test can't be conducted. For the Cross Hole Sonic Logging (CSL) test, steel or plastic pipes of a typical 2" (51mm) diameter are cast into the shaft. These access tubes are immediately filled with water upon completion of the shaft. For CSL testing, steel access pipes are preferred as they don't typically suffer from de-bonding with the concrete as can happen with plastic access pipes. The CSL test entails inserting an ultrasonic transmitter into an access tube and a receiver into another access tube for a particular shaft. The transmitter and receiver are lowered and/or raised at a constant rate while keeping the transmitter and receiver parallel to one another. The transmit frequencies are typically 40 KHz to 70 KHz. Knowing the tube spacing at the surface, the arrival times for the received signals are converted to wavespeed (tube spacing's are measured at the surface and assumed to be constant throughout the length of the shaft). Additionally, the received signal energy can be an indication of concrete quality or an anomaly within the pile. The CSL test is limited in that it only provides an indication of concrete quality between the access tubes which are scanned. Scanning all access tube combinations will give a fairly accurate assessment of the pile core but the CSL test cannot scan outside the access tubes which are located on the inside of the reinforcing cage. Thus the concrete cover cannot be determined with the CSL method.

The CSL access tubes can also be used to perform a gamma-gamma logging (GGL) test. In this GGL test, a probe typically containing cesium-137 (a radioactive material) is lowered into the CSL access tube. The GGL probe will emit particles which are transmitted through the concrete to a photon counter which determines the density of the adjacent material through which the particles passed. This test can scan in 360 degrees around the access tubes so there is some testing of the concrete outside the reinforcing cage, but the sensing range is limited to perhaps 3 inches (76 mm) as the energy is halved every two inches (51 mm). This test will scan less than 20 percent of the pile cross-section in all cases and for large diameter shafts, this test will scan less than 10 percent of pile cross-section (figure 1).

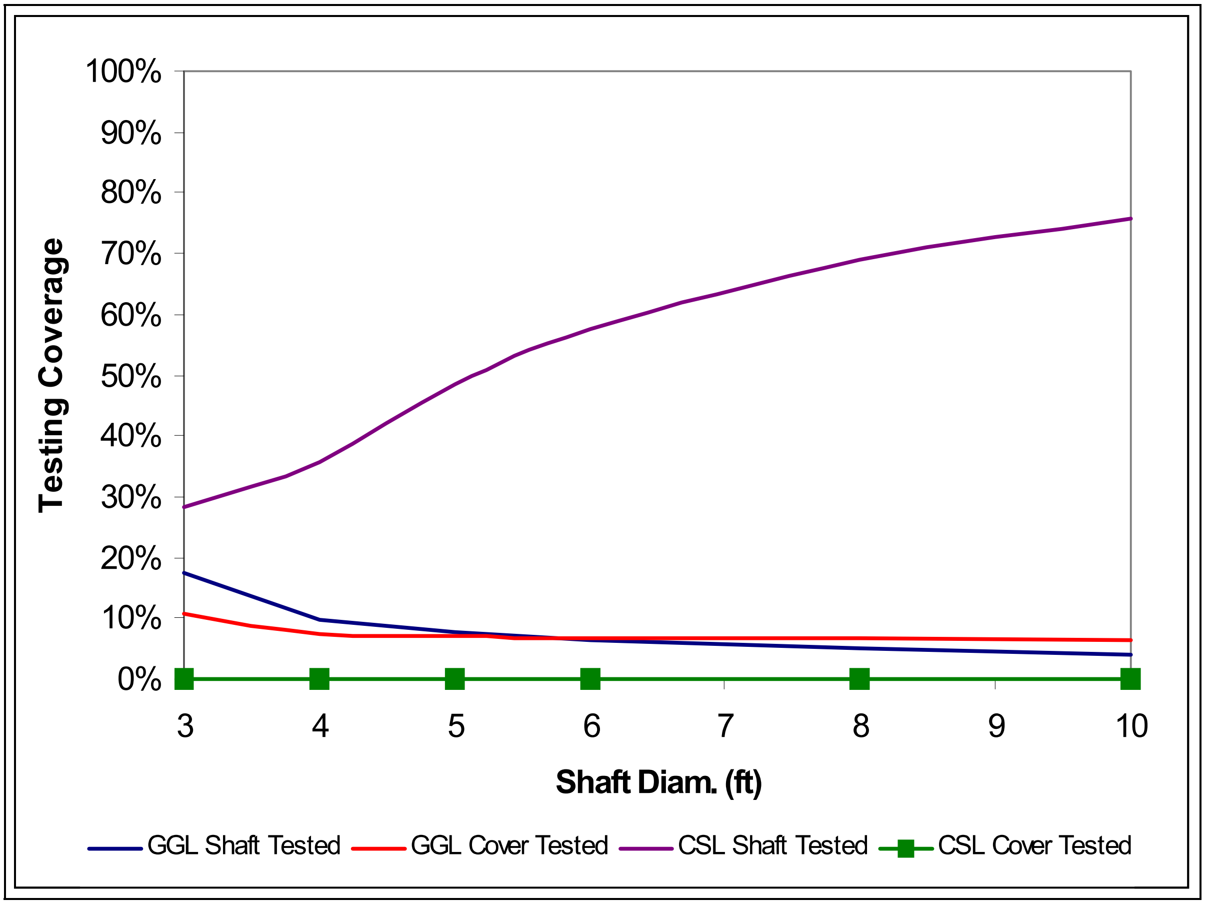

Figure 1

Each of the above mentioned test methods can be successfully used to help determine the integrity of drilled shafts, but as noted in the previous text, each test method also has limitations associated with it. The Thermal Integrity Profiler (TIP) is a new method that has the ability to overcome many of the limitations that the other test methods exhibit.

Thermal Integrity Profiler

The Thermal Integrity Profile (TIP) method determines the integrity of a shaft both inside and outside the reinforcing cage by measuring the hydration temperature of the concrete along the length of the shaft. The temperature measurements are made by passing a thermal probe through a de-watered CSL access tube or from embedding THERMAL WIRES® within the shaft. Temperature measurements at the various measuring locations (various tubes or thermal wires) and at a particular depth are all averaged together and used along with the volume data to determine the overall shape of the shaft.

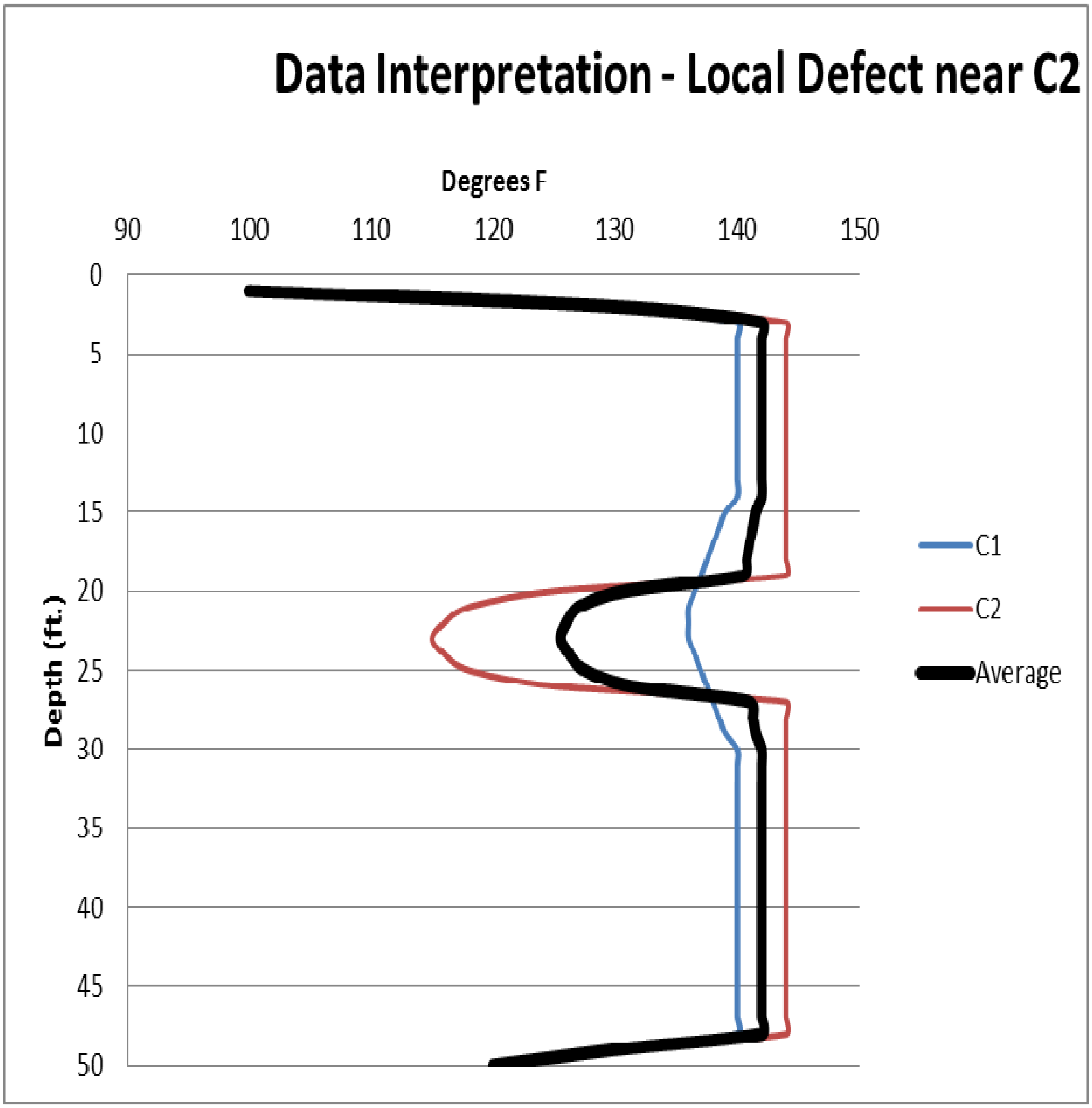

Figure 2

Curing concrete exhibits a normal heat signature dependent upon the shaft diameter, concrete mix design, Concrete quality, and soil conditions. A lack of concrete (defect) will interrupt the normal temperature signature in the area of the defect. This defect will also be seen in measurement locations further away, but the effect at these farthest measurement points is reduced. Any temperature measurements which are cooler than the average are areas of reduced concrete volume (defect) or poor concrete quality and any area with a higher temperature than the average are areas of increased concrete volume (bulge). Figure 2 shows measurements which would indicate a defect located closer to location C2 in this example (normal temperature signature is interrupted greater in measurement location C2 as compared with measurement location C1).

In addition to determining shaft integrity, the TIP test will also reveal any potential issues with reinforcing cage alignment. When comparing TIP measurements from radially opposite locations versus the average value, the cage alignment can be determined. If the first location is cooler or warmer than the average and the radially opposite location behaves in an opposite manner (warmer than average at measurement location two if measurement location one is cooler than average). If measurement location one is cooler than the average this indicates that this location is closer to the surrounding soil while measurement location two is warmer than the average this indicates that this location is closer to the center.

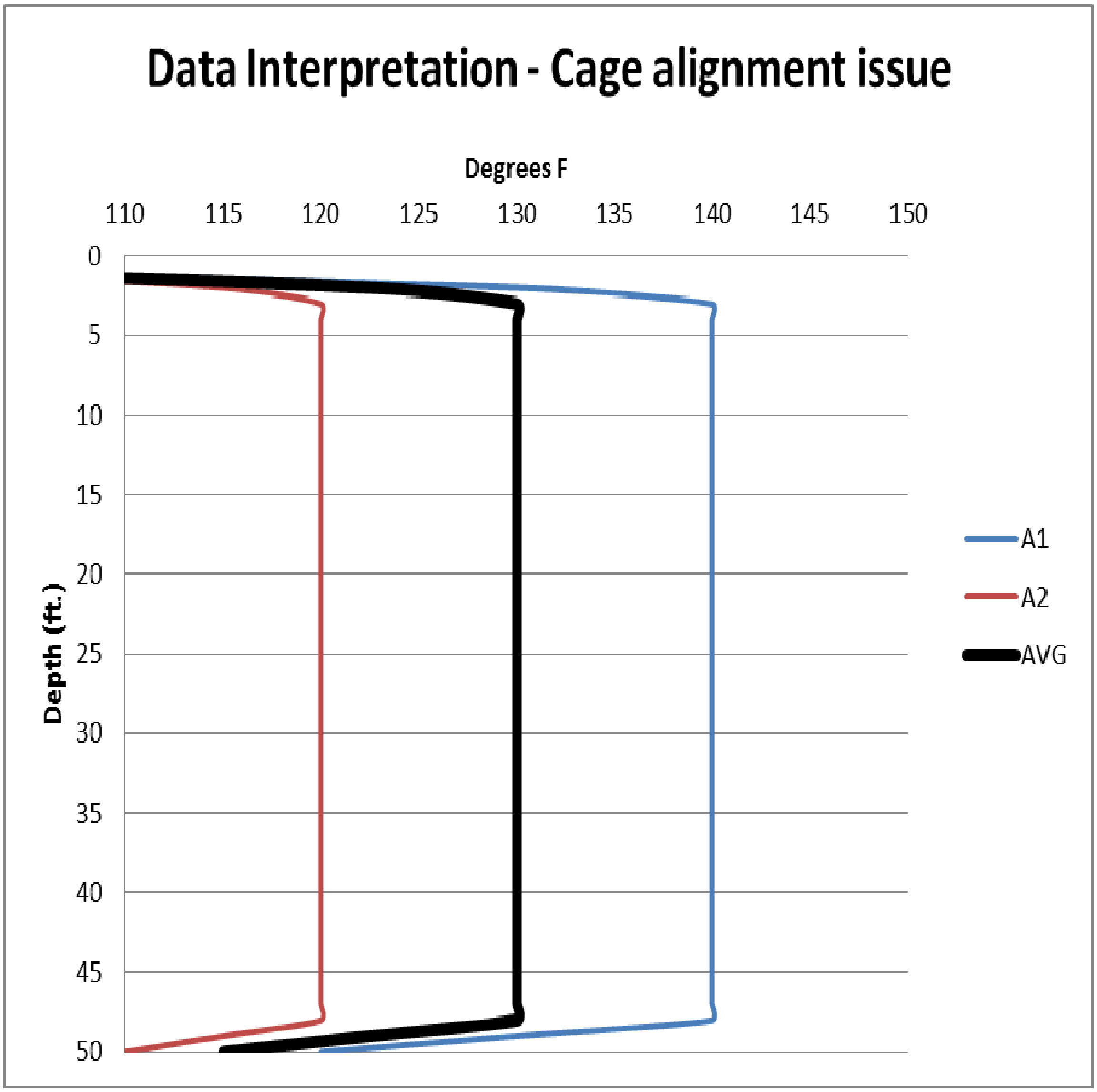

Figure 3

When considering both these measurements together, it can be determined that the cage has shifted such that location two is closer to the shaft center and location one is closer to the surrounding soil (figure 3).

This gives additional information on concrete cover, which can be reduced even without having a defect present. In the example shown in figure 3, location A1 is warmer than average while location A2 is cooler than average, so we can determine that the cage is shifted such that location A1 is moved closer to the Shaft center and location A2 is closer to the surrounding soil (loss of cover at location A2). The recommended number of measuring locations (e.g. access tubes or thermal wires) is one per foot of shaft diameter (e.g. 10 thermal wires installed for a 10 foot diameter shaft) and spaced approximately equal around the reinforcing cage perimeter. The thermal integrity profiler will then easily scan the complete shaft cross-section and any anomalies greater than or equal to 10% of the cross-sectional area will be detected by multiple measuring locations. Anomalies smaller than 10% of cross-sectional area will be detected by the Thermal Integrity Profiler at the nearest measuring location, but these small anomalies are typically insignificant in the performance of the shaft.

The top and bottom of shaft roll off typically seen in a thermal integrity profile has a hyperbolic tangent shape. Knowing this characteristic roll off shape allows for a top and bottom of shaft correction to be applied to the thermal measurements. When the correction is applied to the shaft top and bottom curves, the roll off portion of the curves is corrected to match the interior measurements (curves generally flatten out). Once the top and bottom curves have been adjusted, the analysis in these areas is similar to the remainder of the measurements.

The TIP measurements using a thermal probe require that CSL access tubes be installed in the shaft. These tubes can be steel or plastic. The test will be performed typically 18 to 48 hours after completion of the shaft. The optimum time is dependent upon the shaft diameter and mix design. Large diameter shafts or concrete mix designs that are high in slag will take a longer time to reach peak temperature. The measurement is made by first de-watering the first access tube (water should be stored in a thermal container if CSL testing is to be later done). The probe is then warmed in this water to allow the probe to come to the approximate temperature of the shaft. Next the probe is lowered into the access tube at a rate of no more than 0.3 ft. /sec. recording all temperatures from four infra-red temperature sensors located at every 90^0 radially around the probe. When the first tube is completed, the water from tube two is transferred to tube one and the thermal measurement is taken in tube two. This is continued around the shaft until all tube measurements have been completed. Once the final tube has been thermally tested, the water that was removed from tube one is replaced in the final access tube. There are no de-bonding concerns related to de-watering the steel tubes as the coefficient of thermal expansion for steel and concrete are nearly identical. If no CSL testing will be conducted, the tubes do not require water filled.

An alternate method for measuring the concrete temperatures during the hydration process is to embed THERMAL WIRES into the shaft. These THERMAL WIRES are placed adjacent to or instead of the CSL access tubes (typically one thermal wire per foot of shaft diameter, spaced approximately equal around the reinforcing cage perimeter). The THERMAL WIRES are simply tie wrapped to the vertical rebar members of the reinforcing cage. The thermal measurements are taken automatically at regular time intervals (approximately every 15 minutes) at least until the shaft has reached its peak temperature. One additional thermal wire can be installed in a radial direction with a known and fixed horizontal distance (typically 2- 3 inches (51 – 76 mm)) from another thermal wire. These two adjacent thermal measurements are used to determine the thermal gradient of this shaft. The temperature gradient at the outer portions of a shaft is linear. This measured temperature gradient can be directly applied to any individual temperature measurements to determine effective shaft radius (knowing the temperature change over a known distance and understanding that this temperature signature is linear near the shaft perimeter, we then directly apply this measured gradient to all temperature measurements). When the individual temperature measurement is lower than the average, we can calculate the loss of cover using the measured temperature gradient. Similarly, when any temperature measurement is higher than the average, we can determine the increase in cover using the measured temperature gradient. Using the concrete volume installation records, we can correlate average temperature to average measured volume. Once this average temperature to average volume (radius) correlation has been established, the radius at all points along the shaft can be calculated.

If radially opposite locations in a shaft show one side being warmer than the average while the opposite side is cooler than average, we can use the temperature to volume (radius) conversion or the measured temperature gradient to determine the distance of cage movement.

Bored Pile Thermal Example

In this example, a 66 inch (1.7m) diameter x 179.5 foot (54.2m) long drilled shaft was installed with six plastic CSL access tubes and six thermal wires located near the CSL access tubes. The cage was built as two 100 foot (30.2m) sections and spliced over the hole. The placed concrete was manually logged by the onsite Inspector as shown in figure 4.

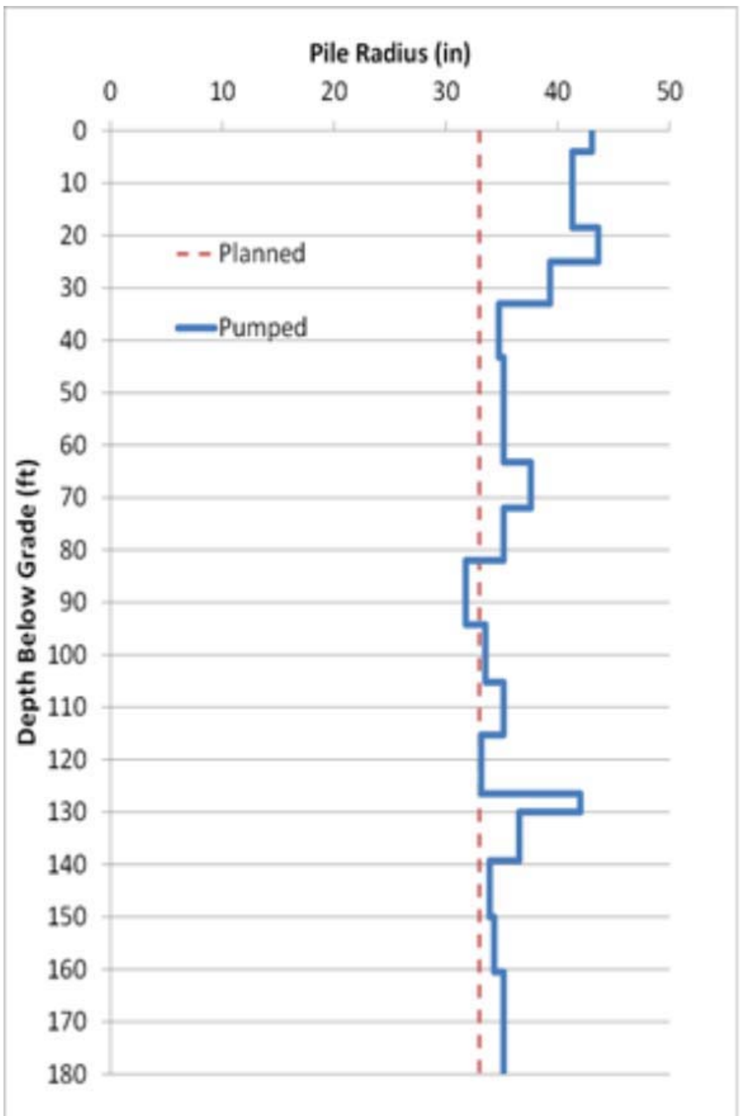

Figure 4

The total volume placed is 191 yds^3. This volume yields an average shaft radius of 36.3 inches. The volume log indicates that the shaft radius is greater than the design radius throughout the shaft. The bulge located at approximately 130 foot depth is due to over-pumping at this location while problems at the batch plant are resolved. The upper 28 feet is oversized as there was an 84 inch diameter temporary casing installed in the upper 28 feet. This is all clearly shown in figure 4.

The drilled shaft was instrumented with six THERMAL WIRES. The wires were attached to the top and bottom reinforcing cage sections and spliced together over the hole. The splice connection used to attach the upper and lower section wires was a simple plug together underwater connector that required minimal effort to mate. The thermal data is shown in figure 5. The thermal data shows no major defects but does indicate that the cage is slightly misaligned from the shaft top down to a depth of approximately 70 feet (wire 2, 3, and 4 are cooler than average while their diametrically opposite wires 1, 5, 6 are similarly warmer than average). Additionally, the oversized shaft diameter in the upper 28 feet is quite obvious as the average temperature is significantly increased in this location.

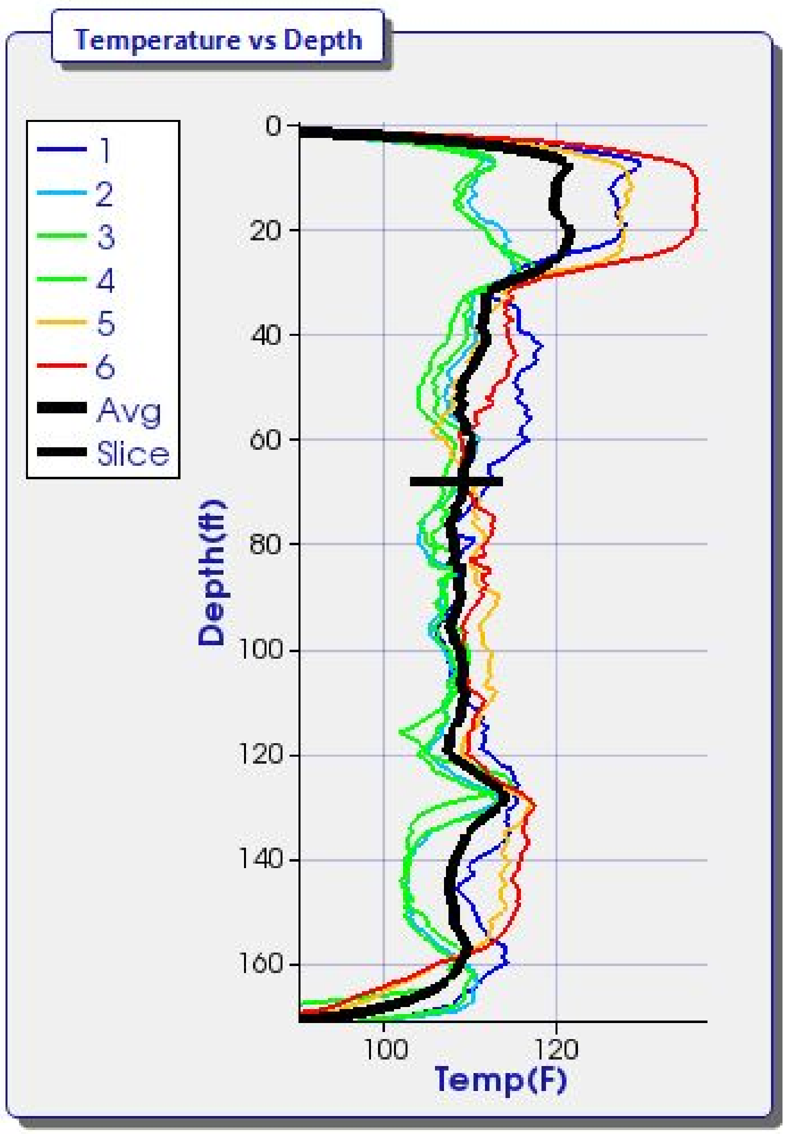

Figure 5

In looking at the shaft bottom data, it is shown that there is a normal one diameter roll off in the temperature data for THERMAL WIRES 1, 2, and 3. The THERMAL WIRES 4, 5, and 6 indicate that there is an abnormal roll off in the temperature data at the shaft bottom, indicating a soft bottom at these locations. This soft bottom extends from approximately 155 feet depth to the shaft bottom.

Figure 6 shows the thermal data and the conversion from temperature to effective shaft radius. The top and bottom roll off shown in figure 5 are corrected in figure 6 by applying a hyperbolic tangent curve to these areas of the thermal data. The data clearly shows that the 33 inch design radius is maintained throughout the shaft. Additionally, the average thermal radius curve has a shape that is very similar to the radius curve developed from the pumping data recorded during installation (figure 4).

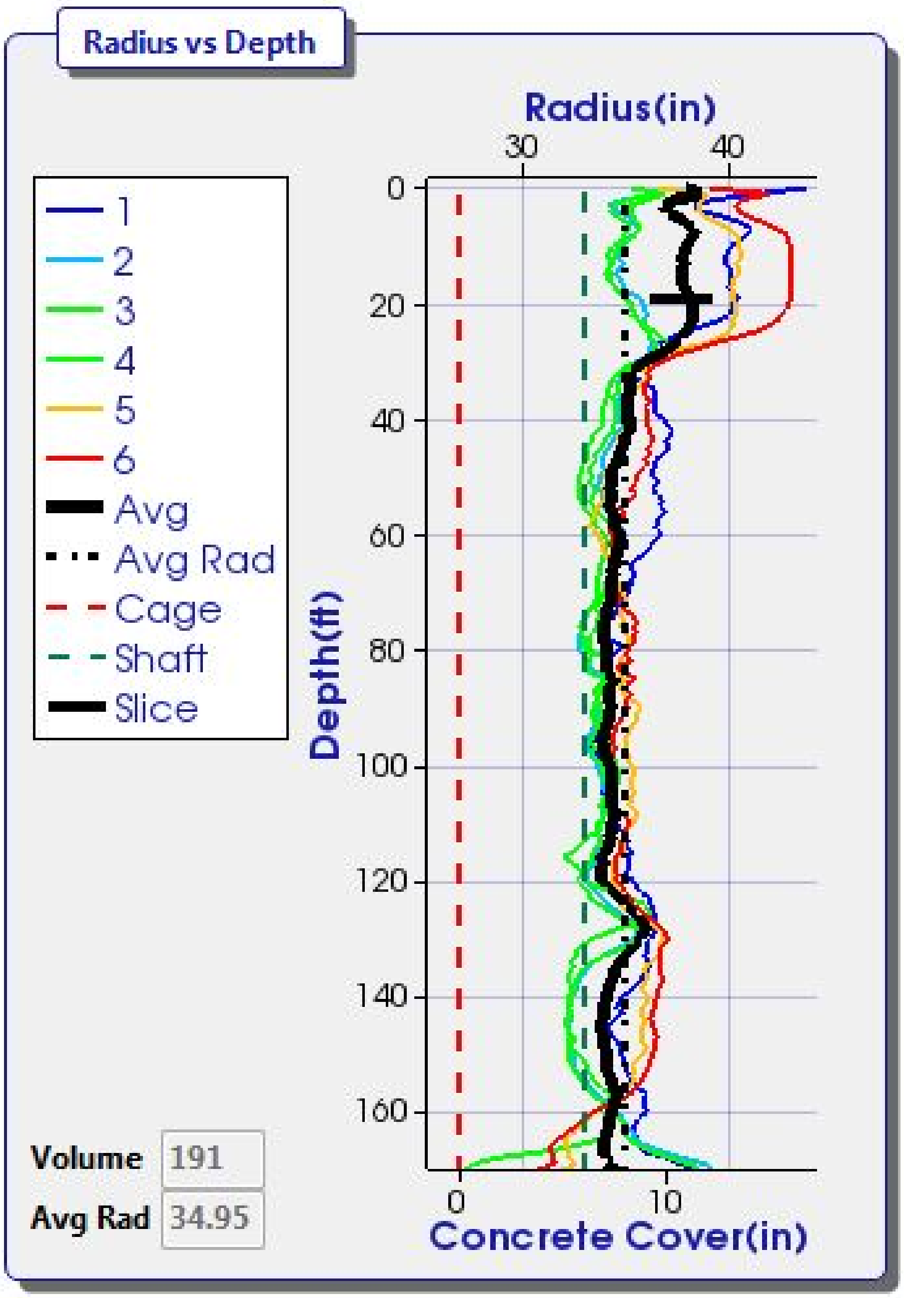

Figure 6

The radius shows a slight increase at a depth of approximately 130 feet due to excessive pumping in this location and the upper portion shows a greatly increased radius where the larger temporary casing was installed (42 inch radius for temporary casing). Looking closer at the individual thermal wire data near the shaft top, it shows that oversized radius is much greater at thermal wire locations 1, 5, and 6. Thermal wire locations 2, 3, and 4 all show an increase in radius in the upper portion of the shaft, but this increased radius is not nearly as significant at the other thermal wire locations, indicating that the increased radius in the upper portion of the shaft is biased in the direction where thermal wires 1, 5, and 6 are located.

Knowing the total volume pumped into the shaft, a 3-dimension drawing of the shaft is created in figure 7. In this view it is quite simple to quickly see all the major details of the shaft including the bulge in the upper portion, slight bulge at approximately 125 feet, and the lack of concrete cover at the shaft bottom.

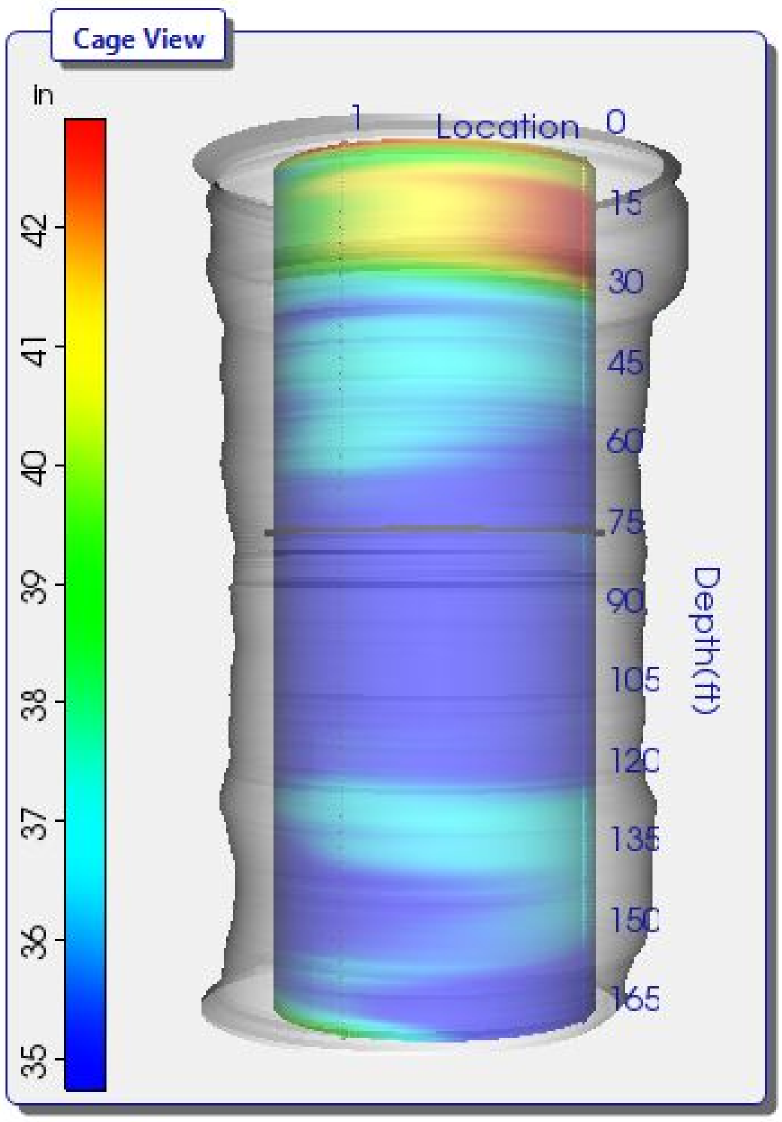

Figure 7

The upper portion of this shaft was later excavated (figure 8) and it is clearly shown that the bulge in the upper portion of the shaft is indeed where the thermal testing had predicted this to occur. The radius for the excavated shaft was measured at the location of the upper bulge and matched quite well with the Thermal Profiling predicted radius.

Figure 8

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The CSL records for this same shaft indicate that there are no problems in any tube scan combinations (figure 9). Figure 9 shows typical CSL results. All scan combinations look similar. The CSL test offers no indication of the concrete cover or cage alignment but simply the integrity of the shaft central section.

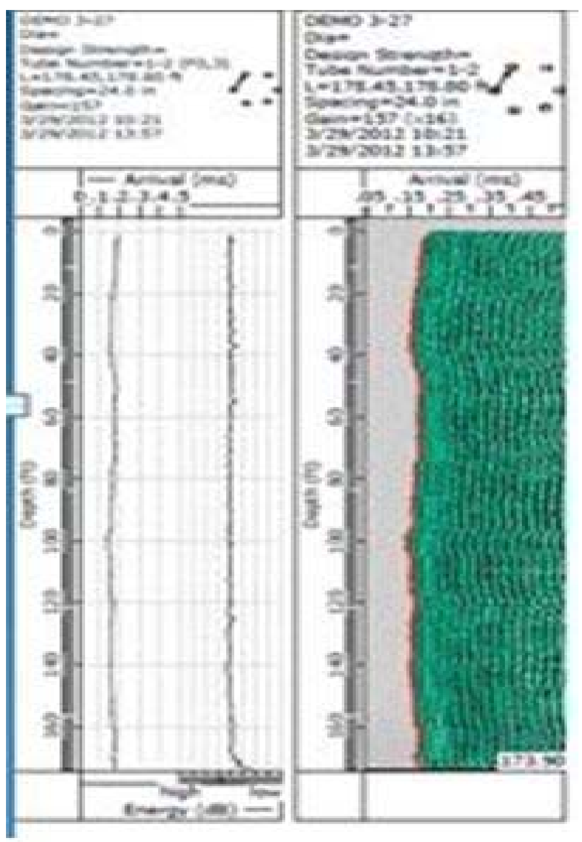

Figure 9

The CSL test results do not indicate that there is a bulge in the upper portion of the shaft, a slight miss-alignment of the reinforcing cage, or a soft bottom around the southwest portion of the shaft. CSL can only evaluate concrete located between tube locations and is incapable of determining shaft integrity outside the reinforcing cage.

CFA Thermal Example

In this example we have several 18 inch CFA piles installed to a depth of 73 feet. The piles were instrumented with a single THERMAL WIRE cable installed on the center reinforcing bar. The instrumented bar was installed in the pile upon completion of the concreting. The THERMAL WIRE cable was installed every sensors spaced every one foot along the extent of the cable. In addition to TIP testing, low strain testing was also performed on several piles. Figure 10 shows the temperature data as a function of depth.

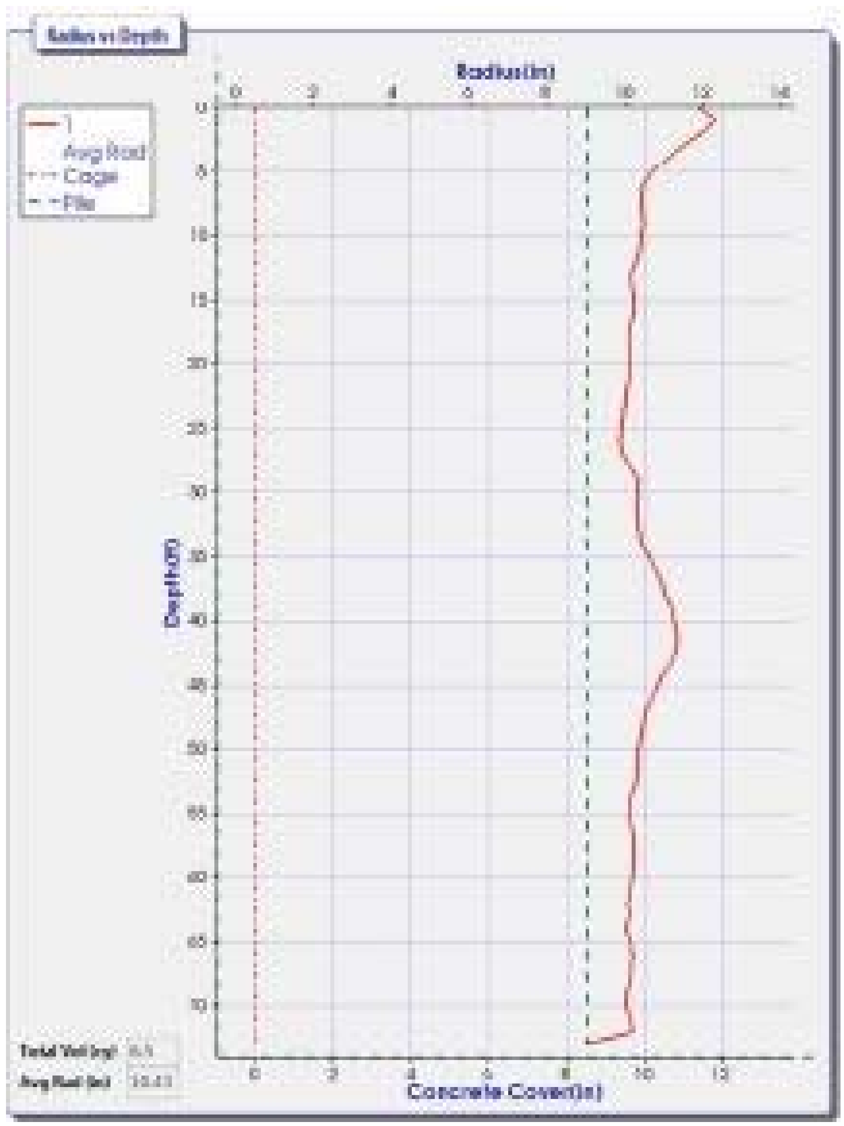

Figure 10

It is quite clear from the data that the increase in temperature at approximately 40 foot depth is associated with an increase in cross section (bulge). The three dimensional view for this pile is shown in figure 11, where the bulge is clearly seen between 35 and 45 feet.

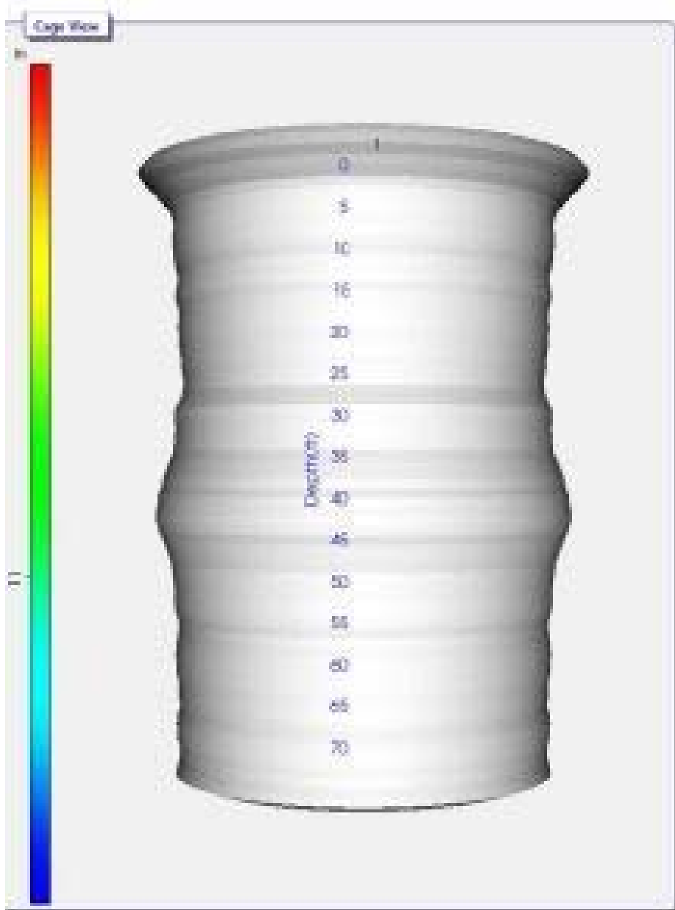

Figure 11

The low strain integrity test result shown in figure 12 does not easily identify the increase in cross section at 40 foot depth and the data indicates that there is a reduction in the pile cross section where the pile is actually returning to its nominal diameter below the bulge.

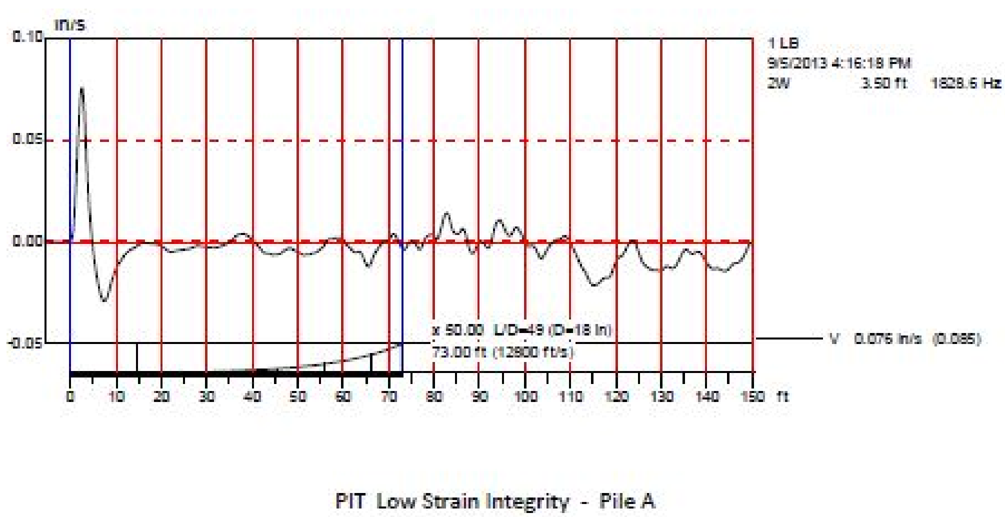

Figure 12

The low strain integrity test result also shows no clear reflection from the pile toe. The TIP result can easily assess the entire CFA pile including the lower sections below an area where there has been a change in pile cross section.

Conclusions

The general trend has been an increase in the use of drilled shafts and CFA piles. These piles are often installed with little or no knowledge of the final shaft integrity. Current non-destructive test methods can each provide partial information as to shaft integrity, but each method also has limitations which don't provide 100% testing of the shaft cross-section. The Thermal Integrity Profile method measures the shaft temperature during the hydration process to make an assessment of the shaft integrity.

From these temperature measurements, the effective shaft radius can be determined. The TIP methods allows for 100% assessment of the shaft cross-section which no other current method can provide. Additionally, the cage alignment can be determined and the concrete cover verified from the TIP data. Since the TIP test is dependent upon the concrete hydration, this results in the TIP test being conducted approximately 24 hours after the shaft has been cast, which is a major advantage over current methods as this can accelerate the construction process.

Test shafts with purposely built in defects located both outside the reinforcing cage as well as within the reinforcing cage have been constructed and the defects have been easily determined from the TIP test. Many field tests have been successfully conducted and comparisons have been made with other available methods. The TIP test provides an overall look at the shaft based upon the local heat signature. Unlike current test methods which provide limited shaft integrity information, the TIP method provides the shaft integrity without the limitations associated with other methods, including overall shape of the shaft, concrete cover over entire cross-section, and cage alignment.

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